THE OTDR DETECTOR NOISE EFFECT OF THE PLASMA CURRENT DETECTION IN TOKAMAK-TYPE FUSION REACTORS

Rastislav Motuz
Doctoral Degree Programme (4), FEEC BUT
E-mail: xmotuz00@vutbr.cz

Supervised by: Petr Drexler
E-mail: drexler@feec.vutbr.cz

Abstract: This paper presents a theoretical analysis dealing with the plasma current measurement in tokamaks. A Polarization Optical Time-Domain Reflectometer (POTDR) setup was used, where the general case of non-uniform magnetic field distribution along the sensing fibre takes place. As a sensing medium, a low birefringent fibre has been chosen. The work is based on the numerical simulations in therms of the Jones formalism and takes into account the OTDR detector noise reflecting the measurement error as a function of the plasma current. The measurement performance is evaluated for an ITER-relevant sensor configuration. Simulation results reveal that for plasma currents from the range of 0 to 1 MA, the signal-to-noise ratio (SNR) of 6 dB complies with the ITER requirements. Subsequently, the SNR level of 4 dB satisfies the plasma current range of 1 to 20 MA. The SNR level of 6 dB is achievable in modern POTDRs.

Keywords: POTDR, plasma current, noise, SNR, Rayleigh scattering, backscattering

1 INTRODUCTION

In tokamaks, accurate knowledge of the plasma current is of paramount importance for the reaction's stability control and the safety of the installation.

In reference [1], a measurement method based on the use of a photon-counting Polarization Optical Time-Domain Reflectometer (POTDR) was proposed. The sensor was experimentally tested using a low-birefringent fiber on the Tore Supra tokamak for a current range of 0.6 – 1.5 MA, providing a maximum error of 13.50 %. An important assumption that the magnetic field along the sensing fibre is constant was made, which is indeed correct for the experiments performed at the Tore Supra [1]. However, for the divertor-type tokamaks, for example the WEST and the ITER, the strength of magnetic field along the fiber contour is changing. As a result, the approach developed in [1] is not anymore applicable.

This simulation work investigates the performance of the POTDR setup for a such non-constant magnetic field along the sensing fiber configuration. The D-shape was taken as a representative case for the ITER. The goal is to demonstrate that the plasma current can be reconstructed from POTDR measurements with an accuracy compatible with the ITER performance requirement, with better results than inductive sensors used, such as Rogowski coils, pick-up coils and flux loops [2].

2 SENSOR MODELING

Figure 1 depicts the POTDR setup. An OTDR launches optical pulses through a linear polarizer that fixes the state of polarization (SOP) incident to the sensing fiber, i.e. the fiber section forming a loop round the vacuum vessel (not necessarily circular, semicircular in our example) and therefore subject to a magnetic field. All along its propagation, the optical pulse is continuously attenuated and scattered via the omnidirectional Rayleigh scattering phenomenon. In every scattering point, a part of the scattered light is backscattered and propagates backward towards the source. The power of the backscattered signal is then measured by the OTDR detector as a function of time, after passing through the linear polarizer. The OTDR apparatus displays the backscattered power as a function of the scattering location since the time scale t is converted to a distance z, using $z = \frac{v_g t}{2}$, where v_g is the group velocity. Note that in figure 1, the end fiber represents a magnetic field-free fiber section connected to the output of the sensing fiber.

The fiber was modeled as a concatenation of elementary sections of a length $l\,(1.4\,\mathrm{cm}) \ll L_B\,(400\,\mathrm{m})$ (see figure 2), where the intrinsic linear birefringence and the circular birefringence induced by the magnetic field can be considered constant. L_B is the beat length of the fiber chosen. Each elementary section i can be represented by a Jones matrix $\mathbf{M_i}$ relating its input and output Jones vectors, written by [3]:

$$\mathbf{M_i} = \begin{pmatrix} \alpha_i + j\beta_i \cos(2q_i) & -\gamma_i + j\beta_i \sin(2q_i) \\ \gamma_i + j\beta_i \sin(2q_i) & \alpha_i - j\beta_i \cos(2q_i) \end{pmatrix} \tag{1}$$

where $\alpha_i = \cos(\Delta_i l)$, $\beta_i = \frac{\delta_i}{2}\frac{\sin(\Delta_i l)}{\Delta_i}$, $\gamma_i = \rho_i \frac{\sin(\Delta_i l)}{\Delta_i}$ and $\Delta_i = \sqrt{\rho_i^2 + \frac{\delta_i^2}{4}}$.

$\delta_i = 2\pi/L_\mathrm{B}$ is the linear intrinsic birefringence of the fiber and q_i the angle of its fastest axis. δ_i and q_i do not depend on the propagation direction and are considered identical for each elementary section i. ρ_i is the circular birefringence induced by the magnetic field. It is assumed that the fiber is not twisted. ρ_i is therefore only because of the Faraday effect and depends on the component of the magnetic field aligned with the fiber axis along section i (denoted by B_i) via $\rho_i = VB_i$, where V is a Verdet constant [4].

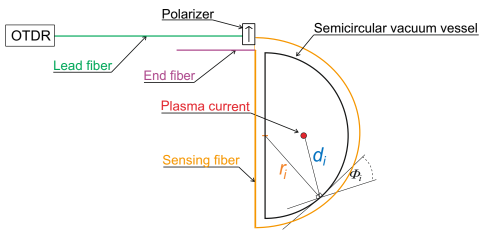

Figure 1: POTDR setup with a sensing fiber placed along a semicircular vacuum vessel.

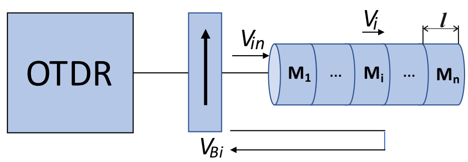

Figure 2: Modeling of the optical fiber.

In the simulation, a semicircular vacuum vessel is considered. It can be seen as an approximation of a D-shape vacuum vessel. The plasma current is considered to be equivalent to a current of intensity I_P, concentrated in the middle of the vacuum vessel's curvature horizontal radius. Calculation ρ_i along the sensing fiber then yields:

$$\rho_i = \frac{V\mu_0 I_\mathrm{p}}{2\pi\,|d_i|}\cos(\phi_i), \tag{2}$$

where the angle ϕ_i reflects the magnetic field strength in particular scattering point of the sensing fiber in relation to the vessel's geometry. d_i is the vector joining plasma current position to scattering point position. r_i is the radius of semicircular vacuum vessel.

3 THE ROUNDTRIP PROPAGATION MODELING

To take into account the round-trip propagation, the boundaries between elementary fiber sections where the Rayleigh backscattering takes place in the modeling are represented by the Jones matrix of a mirror (M_m). When considering the same coordinate system for the two propagation directions, M_m is equal to the identity matrix [5]. In that case, it is also clear that the linear birefringence parameters δ_i and q_i are identical for the two directions. This also applies to the circular birefringence ρ_i due to the non-reciprocal feature of the Faraday effect [6]. As a consequence, the forward and the backward Jones matrices are equal. This is valid because neither twist nor polarization mode coupling are present. The backscattered SOP reaching the polarizer can be therefore written as (see figure 2):

$$V_{B_j} = \left(\prod_{i=j}^{1} \mathbf{M_i} \right) \mathbf{M_m} \left(\prod_{i=1}^{j} \mathbf{M_i} \right) V_{\text{in}} \tag{3}$$

where V_{B_j} is the Jones vector of the light reaching the polarizer input after backscattering at the end of the elementary section j. Without loss of generality, the linear polarizer angle can be assumed equal to 0 i.e. $V_{in} = (1\ 0)^T$.

Finally, the Jones vector of the wave reaching the OTDR detector is given by [5]: $V_{P_j} = \mathbf{M_P} V_{B_j}$, where $\mathbf{M_P} = (1\ 0; 0\ 0)$ is the Jones matrix of the linear polarizer.

The OTDR signal is proportional to the backscattered power P_{B_j} which is equal to $\left|V_{P_j}\right|^2$. By calculating P_{B_j} for every j, the modeling allows generating the normalized POTDR trace $P_B(z)$ (with a sampling distance l) for a given plasma current I_P via equation (2) and a given shape of the vacuum vessel. Note that by setting $V_{in} = (1\ 0)^T$, the input power is set to "1" so that the simulated POTDR trace provides a normalized power versus time.

4 NOISE FLOOR

The previous analysis does not take into account the presence of noise inherent to any OTDR measurement. The SNR (denoted by N) is defined by the difference in dB on the OTDR trace between the maximum level of the backscattered power accordingly: $N = 5\log(\max(P_B(z))/n + 1)$, where n (noise floor) is the RMS (Root Mean Square) level of the OTDR signal with no input backscattered light.

From the knowledge of geometrical dimensions of the vacuum vessel and the plasma current position, a noise free trace – denoted by $P_B(z)$, can be initially calculated via the simulation procedure described above, for every single plasma current of interest. Knowing N, it is then possible to calculate a POTDR trace – denoted by $P_{\text{NF}}(z)$, which takes into account a presence of the noise floor [1]. P_{NF} traces are then stored for plasma current ranging from 1 kA to 20 MA with a step of 1 kA. To obtain $P_{\text{NF}}(z)$, the noise floor n is summed with $P_B(z)$ and the result is then normalized by its maximum value. The random contribution of the detector noise can be done by adding a random component of zero mean to $P_{\text{NF}}(z)$ in a form of Gaussian noise. It is therefore obtained $P_{BN}(z)$, called the noisy trace.

5 THE OTDR DETECTOR NOISE IMPACT IN CASE OF ITER, ANALYSIS AND EVALUATION

According to the ITER specification, the accuracy of the plasma current measurement must be 10 kA for currents up to 1 MA and 1% for current above [7]. The top limit of ITER plasma current is still not firmly known but should not exceed 20 MA [8]. The procedure to study the impact of the OTDR detector noise can be described by the following steps:

1) For given values of I_p and N, a POTDR trace ($P_{BN}(z)$) is simulated in order to estimate the trace that would be measured in such a configuration. **2)** The simulated noisy trace is compared in the logarithm (5 log) scale with the stored curves ($P_{\text{NF}}(z)$, traces taking into account only the noise floor, not the random contribution). The plasma current corresponding to the best fit (in the least square sense) is defined as the estimated I_p, denoted by $\hat{I_p}$. **3)** The relative error in percent is calculated as: $\varepsilon_r = 100\frac{|I_p - \hat{I_p}|}{\hat{I_p}}$. **4)** Steps 1 to 3 are repeated for different noise configuration in order to get the mean relative error and the corresponding standard deviation (STD). The number of realizations is set to 10,000 in order to ensure sufficient statistical sampling. Increasing this number does not provide a significant change of the results.

Figure 3 shows an example. The red curve presents the simulated trace $P_{BN}(z)$ for $I_p = 18.146$ MA and $N = 6$ dB. The green curve represents the stored noise free trace showing the best fit and corresponding to $\hat{I_p} = 18.147$ MA. The fitting gives in this case a relative error of 0.0055 %. Steps 1 to 4 are repeated for every couple (I_p,N) of interest. The first testing I_p's were 1, 4, 8, 12 and 16 MA (high plasma current range 0–17 MA), N ranging from 3 dB to 10 dB with a step of 1 dB. A larger plasma current of 20 MA has also been considered. Moreover, several plasma currents have been simulated, namely 0.10, 0.25, 0.50 and 0.75 MA from the low plasma current range (0-1) MA, with N spaced from 4 dB to 6 dB, also with a step of 1 dB.

Figure 4 shows the mean relative error and its STD for the high plasma current range while figure 5 shows the mean absolute error and its STD for the low plasma urrent range. Figure 6 zooms over a region of interest of the STD graph.

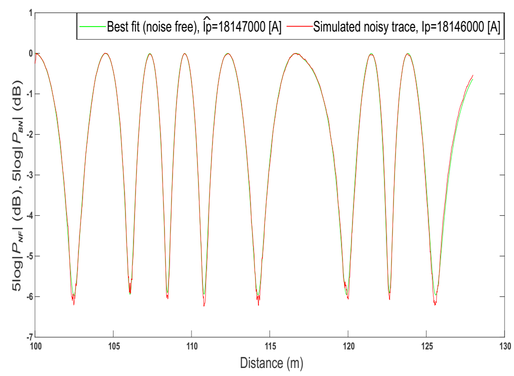

Figure 3: Sensing part of the POTDR trace.

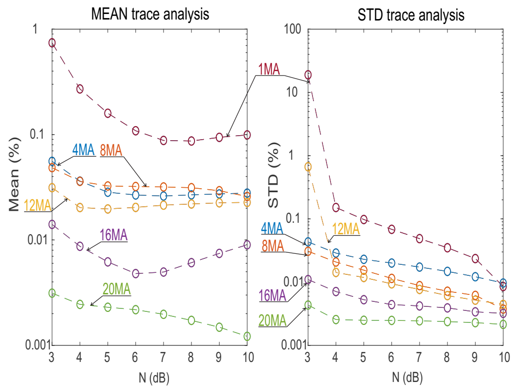

Figure 4: Mean relative error and its STD.

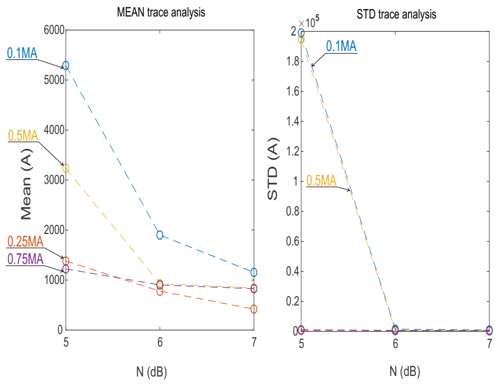

Figure 5: Mean absolute error and its STD – low I_p range.

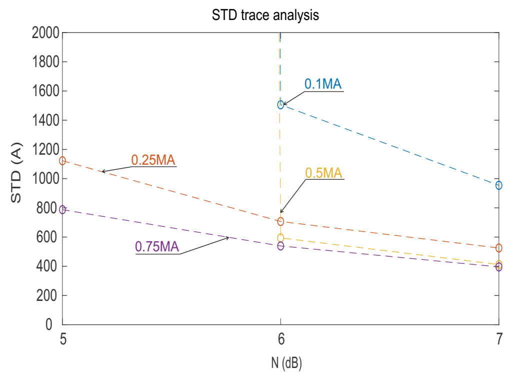

Figure 6: STD absolute error for the I_p and N ranges of interest – zoom of figure 5.

6 DISCUSSION

The results show that the mean error and the STD generally decrease when the plasma current increases. Higher plasma current implies stronger magnetic field and Faraday-induced rotation (equation (2)), which makes the noise contribution less substantial. It was observed, according to the graphical results, that the plasma currents of the range (1 – 20) MA generally complies with the ITER requirements. There is nevertheless an exception, namely $I_p = 1\,\text{MA}$ with $N = 3\,\text{dB}$ for which the relative error exceeds the accuracy limits. The simulation procedure for low range plasma currents showed that the ITER requirement (absolute error under 10 kA) is fulfilled for all currents.

7 CONCLUSION

This simulation investigated in details the detector noise effect on the measurement accuracy, in terms of quantification of the required SNR to meet the ITER requirements. It was shown that the POTDR technique allows to satisfy the ITER requirements for the plasma current measurements. For plasma currents in a 0 – 1 MA range the POTDR must have signal-to-noise ratio better that 6 dB, which can be obtained with modern devices. For currents above 1 MA the requirement for the signal-to-noise ratio can be relaxed to 4 dB. This study constitutes a first step towards the development of a POTDR system dedicated to plasma current measurement in magnetic confinement fusion reactors. In a future, other effects like radiation-induced attenuation, which can significantly affect the sensor sensitivity, will be considered.

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